FATIGUE BEHAVIOUR OF LOW-ALLOY FERRITIC STEEL AND CORRESPONDING DISSIMILAR METAL WELD SUBJECTED TO OXYGENATED HIGH TEMPERATURE WATER

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ABSTRACT
Pressurized components in nuclear power plants (NPPs) operate in high temperature water environments. Deficiencies in considering environmental effects on fatigue in common design standards for nuclear components are controversially discussed. In order to provide a general basis for fatigue design that accounts for environmental effects on fatigue, NUREG CR-6909 provides revised fatigue design methodology where environmental effects from exposure to a reactor coolant environment are considered as a function of strain-amplitude, strain-rate, material type, temperature, and the oxygen content of the water environment. Notwithstanding the experimental basis for the NUREG CR-6909 methodology, there is international consensus that the approach is overly conservative and there is also consensus that there is much scope to optimize the methodology, particularly by the targeted generation of additional data. The current paper reports progress in obtaining better environmental fatigue data for a low alloy ferritic steel (20MnMoNi5-5) used in German NPPs, and for a representative dissimilar metal weld. Following a common methodology, both air and high temperature water fatigue testing is conducted to obtain a specific environmental reduction factor for different loading conditions.

In addition, the formation of, and mechanical behavior of oxide layers have been studied in order to identify and understand the basic mechanisms of environmental fatigue and develop a mechanistic model. Significant conclusions and observations are stated.

Keywords: corrosion-fatigue, environmental effects, low-alloy steel, dissimilar metal weld, oxygenated water, strain-controlled, strain rate

1. INTRODUCTION
Fatigue assessment is an important aspect within the ageing management of safety relevant components in nuclear power plants (NPPs). For pressure retaining components of NPPs thermal loadings are the major cause of cyclic loading. Thermal transients usually result from changes in operational conditions, such as start-up and shut-down procedures related to periodic maintenance. Short term variations in loading resulting from fluctuating power output also lead to increased numbers of fatigue cycles. Locations where stress or strain localisation can occur need special attention [1].

A variety of national fatigue design procedures is available, including a variety of assessment methodologies but all are based on material specific fatigue data depending on the materials being used in NPPs components. For German NPPs, fatigue assessments follow the KTA-standard [2]. The KTA assessment is comparable to ASME-CODE Section III [3]. Neither the KTA, nor the ASME assessments explicitly account for environmental effects on fatigue
behaviour. Investigations have shown that for specific combinations of loading and environmental conditions, design curves, as included in common codes and standards, may not be conservative, even for austenitic corrosion resistant materials [4]. In order to incorporate environmentally assisted fatigue (EAF) effects in the fatigue assessment given by ASME-Code Sect. III, an extensive proposal by Chopra was published first in 2007 [5] and revised in draft in 2014 [6]. Another important development was publication of ASME-Code Case N-761 that provided fatigue design curves for light water reactor environments [7].

Comparable investigations to the work by Chopra et al. have been performed at MPA Stuttgart for specific austenitic stainless steels used in German NPPs in two test campaigns [8] and [9]. Environmental fatigue tests with polished round specimens in oxygenated high temperature water were performed and the results showed a marked decrease in fatigue life compared to air environment tests. However, reductions in fatigue life were less than expected based on data for austenitic stainless steels summarized in [6]. The mean data curves for the German steels were significantly less affected compared to data given in [6]. Most significantly, the number of cycles in to end of life in environmental fatigue tests did not fall below the ASME-design curve. This trend was confirmed by recent research at other institutes [10].

In addition to the testing of austenitic stainless steels, tests have been done by MPA Stuttgart on a ferritic material, a reactor pressure vessel (RPV) low alloy steel (LAS) 22NiMoCr3-7 used in German NPPs [11]. The results were only in partial agreement with estimations for fatigue life proposed by ANL [5] and [6]. Discrepancies were found concerning strain rate dependencies where the German material investigated was found to fail at lower cycles for lower strain rates, compared to predictions using the ANL methodology for air environment.

In order to improve the data base for fatigue behaviour of the LASs used in German NPPs a variety of experimental investigations in both air and in a high temperature water environment have been performed. The current paper reports progress in obtaining better environmental fatigue data for low alloy ferritic steel (20MnMoNi5-5) used in German NPPs and for a representative dissimilar metal weld. Following common methodology, both air and high temperature water fatigue testing is conducted to obtain a specific environmental reduction factor for different loading conditions. In addition, the formation of, and mechanical behavior of, oxide layers have been studied in order to identify and understand the basic mechanisms of environmental fatigue and develop a mechanistic model.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Materials

The materials investigated are a ferritic low alloy steel 20MnMoNi5-5 (Mat.-Nr.: 1.6310) comparable to SA 533 Grade B Class1, a stabilized austenitic stainless steel X6CrNiNb18-10 (Mat.-Nr.: 1.4550) comparable to AISI 347 stainless steel and a Ni-base weld filler material NiCr70Nb comparable to alloy 182. The chemical composition is given in Table 1 for the ferrite material, in Table 2 for the austenitic material and in Table 3 for the Ni-base weld filler material. While austenitic and ferrite base materials meet the requirements very well, the chemical analysis of the Ni-base weld filler materials NiCr70Nb shows some deviation to the required composition. This may be due to the fact that specimens used for chemical analysis of the weld material were extracted from a welded section where some material mixing between weld and base materials can have occurred (dilution effects).
3. FATIGUE TESTS

Fatigue tests were performed using round specimens with a diameter of 10 mm, Figure 1. Tests were performed under strain-control with fully reversed loading sequence \((R = -1)\). Test conditions, in terms of strain amplitude, strain rate and temperature have been chosen such that the effect of the environment on fatigue life may be significant [6]. Fatigue tests were performed in air and high temperature water (HTW) environments with otherwise identical test conditions. Strain-rate can affect the fatigue life in both air and corrosive-media environment, for this reason, air and HTW testing conditions must be identical [11]. The test procedure for HTW includes a load free pre-autoclaving period of at least 100 hours corresponding to the initial operation procedure for new components in NPPs.
Table 1: Chemical composition of ferritic low alloy steel 20MnMoNi5-5

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Table 2: Chemical composition of austenitic stainless steel X6CrNiNb18-10

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Table 3: Chemical composition of Ni-base weld alloy NiCr70Nb

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The chemical composition of the HTW is controlled by a water treatment facility providing consistent and constant boiling water reactor (BWR) water chemistry conditions, of 400 ppb dissolved oxygen and an electrical conductivity $\kappa < 0.15 \mu$S/cm. Previous tests have shown that stress-corrosion-cracks (SCC) can be caused by placing clip-gage tips on the test-diameter of the specimen surface in corrosive environments. The SCC associated with the contact points leads to significantly lower number of cycles to failure in a fatigue test. Consequently, strain-measurements in high-temperature water are based on a contact-free measuring technique within the autoclave. The autoclave system consists of an air, and a water autoclave which are geometrically very similar. Different heating mechanisms are used due to the fact that in air environment a lower heat transfer coefficient requires more heating capacity. To be able to measure the strain within the testing diameter by use of a clip-gage in air environment a fully sealing of the autoclave is not applicable, Figure 2.
First a set of calibration tests in air environment was conducted. Strain-control is realized by use of local clip-gage-measurement. In addition an integral strain measurement is carried out by use of a linear-variable-amplitude-transformer (LVDT), Figure 2. Based on a calibration curve correlating local displacement in the area of the clip-gage, an integral displacement between the LVDT-positions on top and at the bottom can be established. Fatigue tests are performed by use of the integral displacement using the calibrated correlation function. Applying the described testing-methodology, identical test conditions for air and HTW environment are achieved.

Finally, an environmental fatigue life reduction factor $F_{EN}$ following the methodology given by Chopra [6] will be derived, Eqn. 1. With respect to other investigations [12] it seems reasonable to derive $F_{EN}$ from fully identical test conditions (temperature, strain rate) in air and high temperature water environment only.

$$F_{EN} = \left( \frac{N_{\text{air}}}{N_{\text{water}}} \right)$$  \hspace{2cm} \text{Eqn. 1}

In order to extend the knowledge base for different fatigue life influencing factors in air and HTW environment a variation of different test-parameters has been realized in the test setup, Table 4.

### 3.1 Low alloy steel (20MnMoNi5-5)

The specimens were taken from a pipe segment $\varnothing$ 800 mm in axial direction, Figure 3. The circumferential distribution of strength properties was found to be homogeneous. The specimens were cut, turned and polished to achieve a surface quality with a mean surface roughness of below 1.5 µm.
3.2 Dissimilar metal weld

The dissimilar metal weld consists of LAS 20MnMoNi5-5, Ni-Base weld alloy NiCr70Nb and austenitic stainless steel X6CrNiNb18-10, Figure 4. Since the different types of materials have highly varying strength properties the gauge section of the specimens was fully placed in the area of the welded section, Figure 5. To be consistent with the specimens made from homogeneous pipes of LAS 20MnMoNi5-5 the welded specimens were also fabricated with a surface quality of mean surface roughness below 1.5 μm.
Figure 4: Composition of dissimilar metal weld

As a result of the welding process local defects are more likely to appear within a specimen. Specimens where major defects like pores were macroscopically visible on the surface have not been included in the fatigue test.

Figure 5: Location of fatigue specimens within Ø 300 mm welded pipe
4. EXPERIMENTAL RESULTS

4.1 Deformation behaviour in Air

The cyclic deformation behaviour is mainly characterized by cyclic hardening or softening during cyclic loading of a material. Generally soft-annealed materials tend to undergo cyclic hardening and cold worked materials tend to show cyclic softening. For piping materials which are primarily loaded by thermal transients small strain rates and comparatively small amplitudes are usually appropriate for fatigue life assessment.

![Stress-strain-hysteresis of a stabilized cycle for different temperatures and strain rates in air environment](image)

**Figure 6:** Stress-strain-hysteresis of a stabilized cycle for different temperatures and strain rates in air environment

4.2 Low alloy steel (20MnMoNi5-5)

The deformation behaviour of LAS 20MnMoNi5-5 was found to be sensitive to strain rate and temperature, see Figure 6. For a strain amplitude of $\varepsilon_a = 0.25\%$, a strain rate of $\dot{\varepsilon} = 0.04\%/s$ gave slightly greater hardening compared to a strain rate of $\dot{\varepsilon} = 0.4\%/s$. Also comparing test temperatures 240 °C to 150 °C, hardening is slightly greater at the higher temperature. This trend is in good agreement with test results of similar LAS tested at MPA Stuttgart [11] but opposite to the behaviour described by ANL [6].

4.3 Dissimilar metal weld

The specimens made from the dissimilar metal weld are tested at $\varepsilon_a = 0.30\%$ and show a minor initial hardening behaviour from 400 MPa to 425 MPa. Although the welded section is a highly inhomogeneous built up section as result of the high number of weld passes, the fatigue behaviour is found to be very homogenous with a small scatter in the stabilized stress-strain-relation, Figure 7.
Figure 7: Stress-evolution in three strain controlled fatigue tests of welded specimens

5. FATIGUE LIFE IN AIR AND HTW

Failure criterion to evaluate fatigue life was a load drop of 25 % based on the steady state stabilized behaviour. All materials investigated exhibited distinctive stabilized fatigue behaviour over more than 80 % of the testing period. Results for LAS and welded specimens are included in Table 4.

5.1 Low alloy steel (20MnMoNi5-5)

Besides hardening behaviour also fatigue life was found to be sensitive to both strain rate and temperature in air environment. For an increase in loading rate by a factor of 10 at 240 °C an increase in fatigue life was found to be in the range of 1.6 for air and 3.9 for HTW environment. Clearly this discrepancy demonstrates that in order to derive valid environmental factors, one needs to consider material specific strain rate sensitivity to yield a physically valid environmental factor. This stands in contrast to what is published in NUREG 6909 [6], where the strain rate effect in air environment is not considered for LAS. Neglecting the strain rate effect an environmental factor $F_{EN}$ of 10.8 instead of only 6.6, is calculated. A change in test temperature from 150 °C to 240 °C resulted in an increase in cycles to failure in an air environment, but inversely, a decrease in cycles to failure in HTW environment. Based on NUREG 6909 [6] a lower boundary for environmental effects at $T \leq 150$ °C is specified with $F_{EN} = 2.0$. Within this research $F_{EN}$ was found to be 3.0 at 150 °C. Regarding higher strain amplitudes, $\varepsilon_a = 0.35$ % compared to $\varepsilon_a = 0.25$ %, $F_{EN}$ tends to decrease with increasing strain amplitude.
5.2 Dissimilar metal welds

Before reporting results of the fatigue tests on weld metal, it is important to note that no specimens with known weld defects were included in the program. Also, none of the initially surface-defect-free specimens failed prematurely due to buried weld defects influencing. Fatigue life for dissimilar metal welds in air environment at 240 °C at a strain amplitude of $\varepsilon_a = 0.30 \%$ with a strain rate of 0.04%/s was determined to be in average at about 22184 loading cycles, Table 4. For HTW environment fatigue life was found to be at about 16121 loading cycles. Based on NUREG 6909 [6] for NiCr-ferrous alloys under the given environmental and loading conditions, $F_{EN}$ is predicted to be 1.3. Within this research $F_{EN}$ was found to be 1.4 for the given conditions.

6. OXIDE LAYERS IN HTW

Oxide layers have been studied for various types of materials in combination with different types of environment like air, water or steam in numerous research projects. In steam environments, oxide layers can grow to thicknesses up to several tenths of millimeters, depending on the materials, the chemical composition of the environment and the mechanical loading scenario, [13] and [14]. Such layers are comparatively thick and can be investigated in cross-section by means of optical microscopy and scanning electron microscopy [13]. In contrast, the thickness of oxide layers grown on ferritic steels in oxygenated HTW are thinner and characterization requires electron microscopy, and the capabilities of electron microscopy are greatly enhance if combined with a focused ion beam attachment to facilitate specimen extraction and preparation. Oxide layers on low alloy or carbon steels are generally known to consist of an inner fine grained and outer coarse grained oxide layer, Figure 8. The inner oxide layer grows along the former metal grain structure and is comparatively dense. The outer oxide layer grows on top of the former metal surface and is fed by diffusion processes of hydrogen ions being transported into the base metal and metal-ions being dissolved out of the base metal structure. In oxygenated HTW environment both oxide layers mainly consist of oxide-species magnetite which is formed by Schikorr-reaction [15]. The properties of protective oxides on ferritic steels are thought to be influential in their cracking behaviour in HTW environments. In general mechanical behaviour of oxide layers is very brittle compared to the metallic base material. Experimental investigations presume that threshold strains for cracking of protective oxide layers exist [16],[17] and [20]. The values taken from literature exhibit a big scatter for critical strains and it may be concluded that the threshold values are very sensitive to both test conditions and the material.
6.1 Formation

Investigations focussed on the ferritic material where environmental effects are generally more pronounced and oxide layers are expected to be mechanically less stable. A macroscopic overview and comparison of the different types of oxide layers on the different types of materials in air and HTW environment is given in Figure 9.

The characteristics of oxide layers were investigated with regard to the surface topology of grain structures, by viewing in cross-section using a scanning electron microscope. To facilitate characterizing oxide thickness and its layered structure, a focused ion beam (FIB) facility attached to an electron microscope was used to prepare cross sections. In addition to the fatigue tests some plain specimens were only pre-autoclaved and afterwards analysed. The surface topology and the FIB-Cut through layers are shown in Figure 10. At the end of the fatigue tests (25% load drop) the specimens were sectioned and analysed by scanning electron microscopy.

The surface topology of the ferrite specimens in HTW tested at strain amplitude $\varepsilon_a = 0.25\%$ is shown in Figure 11 for different strain rates. At $\dot{\varepsilon} = 0.04\%$/s the magnetite grain structure looks somewhat finer and magnetite grains seem less merged compared to $\dot{\varepsilon} = 0.4\%$/s. At the higher strain rate of $\dot{\varepsilon} = 0.4\%$/s the overall magnetite size is topologically bigger and magnetite spinels form less pronounced edges.

In addition to topological analysis, FIB-cut cross-sections were made and examined for some of the specimens with strain amplitude $\varepsilon_a = 0.25\%$ at different strain rates, Figure 12. At the lower strain rate of $\dot{\varepsilon} = 0.04\%$/s the overall oxide layer thickness is clearly thinner compared to the test with $\dot{\varepsilon} = 0.4\%$/s. Based on these results a distinction between inner and outer oxide layer is not visible in the case of the lower strain rate but can approximately be derived from the higher strain rate. Obviously the grain size of the magnetite grains grown on the outer oxide layer during faster cycling is significantly bigger. These results indicate that the strain rate dependent deformation behaviour of the ferritic base metal may directly influence formation of the
magnetite oxide layer. Overall, the thickness of the oxide layers tends to be somewhat thinner than what is known from literature, [18] and [19]. In contrast to the ferritic steel oxides, oxide layers on the austenite material were found to be very homogenous and clearly below 100 nm in average thickness. The oxide layers look typical for this type of material. In the case of the Ni-base weld material, the oxide layers are mostly similar to the austenite material. The surface was predominantly built up of single small crystals or clusters of oxide-crystals. Due to material mixing (dilution effects) during the welding process local magnetite isles and defects like hot cracks exist, Figure 13.

![Air vs HTW](image)

Figure 9: Dissimilar metal weld after fatigue test in air and HTW

### 6.2 Mechanical behaviour

Values for stress or strain limits for different types of oxide layers given in the literature cover a large range and seem to be highly dependent on, environmental conditions, the base material, the type of component, and its operational loading situation. Most of the oxide “critical-stress to failure” data for ferritic materials is in the range of 100 MPa to 400 MPa in tension, [14] and [20]. In terms of critical strains to failure these were found to be in the range of 0.06 and 0.08 % [20].

Within this research, mechanical behaviour of oxide layers was investigated by use of a static tension test on pretreated specimens (HTW, 100 hours, 400 ppb oxygen) in combination with acoustic emission technique (AET). For the LAS material, cracking within the oxide layer was detected at about 350 MPa relating to 0.15 to 0.17 % of uniaxial strain. Whether the detected acoustic cracking signals correspond to cracking of the inner oxide layer or separation of bigger magnetite grains from the inner layer could not be determined. An analogous investigation on the austenite and Ni-base material was performed. A welded specimen was loaded in uniaxial tension close to the yield strength of the austenite material at about 210 MPa. Analysis with AET did not detect cracking of the austenite and Ni-basis layers. This may be due to the small layer thickness compared to layers on ferrite material and therefore higher requirements regarding the microphone transmitter.
Figure 10: Oxide layers of pretreated LAS specimens without cyclic loading

Figure 11: Surface topology of the oxide layers formed on the LAS during a fatigue test in HTW.

Figure 12: FIB-Cut through oxide layers on the LAS after fatigue test in HTW
Figure 13: Hot crack on the Ni-base weld section (left) and locally grown big magnetite grains as a result of increase iron concentrations (right)
7. DISCUSSION AND CONCLUSIONS

Environmental effects on fatigue behaviour of materials for pressure retaining components are investigated to improve the understanding for mechanical-chemical interactions. This paper is focused on a specific ferritic material typical of the type used for German NPPs, together with a representative dissimilar metal weld.

Results demonstrate that, especially in the case of the LAS tested, generic estimations of EAF in terms of fatigue life reduction factors do not represent test results in a satisfactory manner. Based on a common methodology, fatigue life, even in air, can differ by a factor of about 1.5 for the low cycle fatigue regime between $10^3$ and $10^5$ loading cycles, compared to results in literature [6]. In order to evaluate relative-to-air material behaviour in HTW correctly, it is necessary to consider effects of temperature and strain rate in air as well as in a HTW environment to generate accurate, material specific, fatigue life reduction factors. Merging fatigue data for different types of low-alloy steels together into a single generic database, disregards some, possibly significant, material specific variations in EAF behaviour arising from different mechanisms.

In contrast to the results for the ferritic material, our investigations of Ni-base dissimilar metal weld material EAF behaviour produced results in good agreement with values given in the literature [6], showing only a less than 10% deviation from the expected $F_{EN}$-factor for NiCr-ferrous alloys [6]. Although chemical analysis clearly detected local concentration increases of iron within the boundary layer of the weld, it seems this does not influence the cracking behaviour significantly.

An analysis of oxide layers on the ferrite material shows a distinct correlation between strain rate and the development of oxide layers. In order to establish a mechanistic model of the interaction between base material and oxide layers it is necessary to extend the experimental database of environmental fatigue tests for different loading conditions. To understand the basic mechanisms, such investigations have to be carried out on very homogeneous materials in order to reveal the subtle interactions, and relatively small scale surface effects that are marginal from a general mechanical engineering standpoint, but may be influential in determining EAF behaviour.

8. ACKNOWLEDGMENTS

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9. NOMENCLATURE

EAF Environmentally assisted Fatigue
HTW High temperature water
NPPs Nuclear power plants
MPA Materials testing Institute
University of Stuttgart
BMWi German Federal Ministry of Economic Affairs and Energy
BWR Boiler Water Reactor
LWR Light Water Reactor
ANL Argonne National Laboratory
LVDT Linear Variable amplitude Transformer
LAS low alloy steel
AET acoustic emission technique
SCC stress corrosion crack
FIB focused ion beam
ε strain
σ stress
κ electrical conductivity
10. REFERENCES


